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Ecological accounting for China based on extended exergy

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ABSTRACT

All recent analyses acknowledge that environmental resources are in short supply and that it is on them that "carrying capacity" calculations ought to be based. For the specific case of the Chinese society, which is undergoing an unprecedented period of continuous growth, it seems therefore mandatory to alleviate the conflict between high-speed development and available resources. This paper analyzes the variation of the natural resources input into China during years 2000–2007 using the exergy and extended exergy socio-economic metric. Fluxes of materials, labor, capital and environmental remediation expenses were quantified by a numeraire solidly rooted on a second-law metric, so that a new mode of ecological accounting that quantifies both the composition and the proportion of the extended exergy flows can shed light on the total available energy input into the Chinese society. Two new indicators, labor production efficiency and net pro-capite exergy resource input, are proposed to depict the contribution of economic, social and environmental aspects to the usual four production factors and to express the conversion results in transferring efficiency and quantity from material energy to economic output. "Social" extended exergy analysis, applied to each one of the seven sectors of the society, is suggested as an effective method to reveal the energy quality degradation in the resource conversion process at both national and sectoral levels. The comparison of social resource accounting among different societies by using these two indicators may provide useful additional information to evaluate the production conversion coefficients, to assess the environmental impacts and to diagnose possible ecological dysfunctions. In addition, the extended exergy analysis of the Chinese society is helpful in uncovering the long-term resource depletion and promoting efficiency of the resource transformation in the social–economic–environmental system, thus providing a holistic method and a systematic view for decision makers responsible for environmental management.

Contents

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1. Introduction

Exergy, defined as the maximum work performed by a system in the process of reaching equilibrium with its reference environment while undergoing only reversible processes and interacting solely with the environment itself, is widely used in the fields of process optimization, resource accounting and environmental impact assessment, because it provides a rational and rigorously founded thermodynamic quantification of the consumption of natural resources, environmental losses, and ecosystem degradation.

Being closely related to use value, which is a central concept in macroeconomics, exergy has already been combined with economic analysis methods to quantify the cost of the exergy destruction and losses and hence the cost of products, thus optimizing various stages of the life cycle of a product to facilitate decision-making procedures [1–6]. Capitalizing on earlier work by Tribus and El-Sayed [7], Gaggioli [8] and Szargut [9], Tsatsaronis [5], and Valero et al. [10–12] proposed the theory of Exergetic Cost based on both economic and thermodynamic aspects: their costing method has been later [13–15] expanded to include meaningful analyses of the relationship between the human species and nature. In the works of Ayres, Cornelissen and Szargut, the 'exergo-ecological cost' is proposed as a complementary tool for the exergetic life cycle analysis [16–18], to calculate the exergy consumption throughout the life cycle of a product or service, the environmental emission abatement process, and the technological process of material replacement [19]. Szargut et al. [20] recommend cumulative exergy consumption (CEC) as an ecological indicator to quantify the loss of exergy of resource deposits over time connected with the fabrication of a commodity. Pioneered by Reistad and perfected by Wall, exergy analyses of the entire Nation have been performed: this method considers the whole society as a huge "transformer" that consumes resources from and discharges waste into the environment via its various production sectors and consumption terminals [21–23]. A series of similar analyses has been performed for different sectors and countries [24–36], to uncover the underlying productive structure of societies in a strictly thermodynamic sense and to identify their potential towards increased thermo-economic efficiency [37,38]. In general, the purpose of such societal resource exergy accounting is to identify the priorities of developing/restructuring specific sectors and establishing a better resource management mode. Exergy analyses attain this goal by quantifying the cost of the exergy destruction of use value and by suggesting ways to improve the resource utilization efficiency of the relevant conversion processes at different time and space scales, from resource base to the final use and disposal.

Ecosystem products and services can also be incorporated into the exergy accounting framework. Bakshi and his group [39] combined the methods of process systems engineering, systems ecology and life cycle assessment with a contamination of exergy and energy analyses, to include the ecological inputs and the impact of environmental emissions. In an attempt to bridge the gap between industrial ecology and systems ecology, Hau and Bakshi [40] developed a novel network and allocation algebra to expand the Cumulative Exergy Consumption (CEC) analysis into Ecological Cumulative Exergy Consumption (ECEC). Ukidwe and Bakshi [41,42] quantified the ecosystem contribution to the industrial economy by means of a case study of the US economy and subsequently employed the thermodynamic input–output analysis for the integrated economic-ecological-human resources system [43]. More details on studies of the ecosystem contribution to the industrial supply chain can be found in the critical reviews of Dewulf et al. [44] and Gasparatos et al. [29].

Exergy has been also considered as a goal function or "orientor", and adopted to identify the status, stage and trend of ecosystem growth and development [45–48]: the idea is that ecosystems will survive that are capable of either storing a higher amount of exergy than their competitors or of being able to adjust their configuration in such a way to maintain themselves in a permanent far-from-equilibrium state [49–55]. Because physical exergy is not a suitable indicator in the ecosystem context where boundary growth, biomass growth, network growth and information growth are the most important parameters, eco-exergy has been proposed by Jørgensen [45] to measure the available energy invested or information coded by an ecosystem in building and maintaining its structure in a far-from-equilibrium state. This is also in accordance with the environmental philosophy suggested by Rolston and Chaitin, that the value of a biotic system can be found both in the stability of the system and in the amount of information or the DNA of the species it contains [56]. Eco-exergy measures contrast, i.e. the tendency to move away from the inorganic soup associated with the increase of exergy flows (maximum capture) and decrease of exergy losses (maximum efficiency) [57,58]. Several case studies have been presented on aquatic ecosystems [51,59–64], with emphasis on the ecological buffering capacity and other global performance parameters [45,65–71].

Extended exergy, first proposed in 1999 [72], is an extension of traditional exergy analysis to include two of the primary production factors considered in neo-classical economics (labor and capital) into an exergy analysis, thus bridging the gap in the way 'production of value' is quantified in Economics and Thermodynamics [73]. EEA retains the fundamental assumption that the cost of a product or service is expressed as a compound function of the production factors, but it is the first theory that uses an additive exergy metric to make these factors homogeneously quantified in terms of the value production chain associated with the production. Particular emphasis is placed by EEA on labor, which is seen as "the" unique driver of the whole value production chain and the generator of surplus value in each sector of the chain. In contrast with previous quantification of labor in terms of monetary considerations, the extended exergetic content of labor is defined in terms of the social–economic, production, technical and environmental management factors through exchange of commodities produced by labor and by labor-generated capital. In essence, EEA is a socio-economic construct with biophysical references, intended to reconcile the labor theory of value and the current thermodynamic theory: therefore, it can be used as a goal function to optimize the allocation and distribution of resources in the difficult transition from the present state of affairs to a long-term sustainable society. EEA is a suitable tool to measure the cost

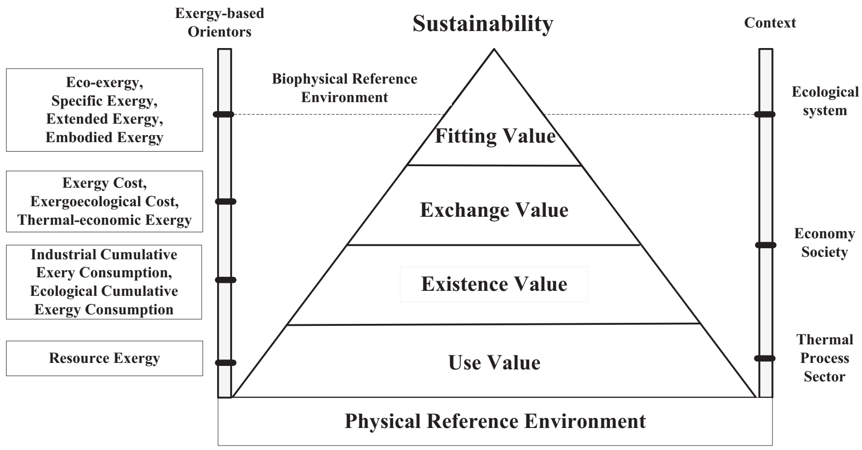

Fig. 1. The value pyramid.

of sustainability, since it is well known that most measures aimed at increasing the degree of sustainability of a society require greater resource consumption at the onset [74].

To better understand different exergy-based indicators, we present the value pyramid in Fig. 1 to describe the value formation during the production process and the cost for sustainability corresponding to the value category in specific context. Specifically, we suggest the following classification:

(1) The *use value* of a commodity is defined as the raw exergy content of its constituents: this is measured by a resource exergy analysis that measures the resource availability with respect to a well-identified physical and biophysical reference environment. For example, the use value of a mineral ore is its exergy content in the ground, the use value of solar radiation is its irradiation exergy, etc.
(2) The *embodied value* is equivalent to Szargut's Cumulative Exergy Content, and measures the sum of the exergy of all of the energy and material flow inputs that contribute to the production process, from extraction to disposal. These inputs contribute to the value accumulated in the forming and 'existence' process of the product, which can also be termed as *existence value.*
(3) Besides exergy input, there are two other essential production factors, labor and capital. Both are linked – for what their quantification is concerned – to the economic exchanges occurring in the market and in the society: thus we can consider an *exchange value* that reflects the economic production and consumption structures and that may vary over time with the socio-economic texture of the society.
(4) If we include in the analysis the end pipe of the production process, i.e., the remediation and buffering activities needed to fit the production chain into the surrounding environment and in the whole biosphere in such a way that an overall "minimal damage" is caused, it is necessary to introduce yet another value measure, namely the *fitting value*, which is directly related to the sustainability of the system inserted into, and interacting in the short and long term with, the supporting environment. Notice that the fitting value is closely related with the orientor, goal function or directionality of the ecosystems. With exergy-based orientors and the underlying fitting value, we can adopt a forward-looking approach to explain the growth and development of the ecosystem (i.e., to describe the present interactions and behaviors of the ecosystem based on the presumed rationality and intentional stance associated with belief and desire), which is quite different from the pseudo-causal explanations of all backward-looking methods. This is particularly important if the biophysical reference environment is brought into the picture. Consider that an ecosystem exergy – however defined – must quantify the potential trends generated from the inside of the system [54,55], whereas all current exergy-based orientors measure the trends with an input–output approach, possibly introducing "exergy storages" to account for time-related imbalances. Fath et al. [49] probed into 10 long standing goal functions (organizing principles) and concluded that all of them were in fact mutually consistent in view of ecological network paradigm. In our opinion, these principles must be integrated into a 'context', within which the specific principle can be fully understood and correctly used: specifically, we argue that while eco-exergy may be better suited for describing the evolution of ecosystems (see Fig. 1), EEA is a better global tool to assess the development of the socio-economic system, and therefore includes – so to say – the former. Given the above system of values, the cost of sustainability can be calculated with an exergy-based quantifier: the higher the cost (the "cost" here refers to ecological cost, contains resource depletion, economic input and environmental impacts, which determined by social consuming structure), the more unsustainable the production (development) mode is. In doing so, the principle of struggle for existence, previously quantified as struggle for available "excess" free energy [75], and in terms of the lowest requirement for life to exist, can be reformulated as struggle for the least extended-exergy cost, that contains all of the four values associated with sustainability issues. The levels of various exergy-based indicators are also represented in Fig. 1.

Related case studies that have acknowledged EEA as a useful tool for societal accounting have covered Norway [37], Italy [76,77], UK [78], the Dutch energy sector [79], and the US [80]. In this study, EEA is applied to a time-series analysis of the Chinese society (2000–2007) and certain modifications in the context of the China's economy embracing extraction, conversion, agriculture, industry, transportation, tertiary and households sectors. A comparison with traditional exergetic accounting results is also offered: the hierarchical structures of the Chinese society are compared based on both exergetic and extended exergetic metrics.

2. Methodology

2.1. Method

Extended-exergy (EE) values are assigned to labor and capital fluxes in addition to thermomechanical and chemical exergy

Table 1
The values of the raw exergy of each component.
Source: [25,82,83].

Item	Value	Unit
Coal	22.2	10^6 J/kg
Coke	29.9	10^6 J/kg
Petroleum	44.3	10^6 J/kg
Natural gas	4.1	10^4 J/cu.m
Electricity	3.6×10^{-1}	10^4 J/kWh
Rice	15.8	10^6 J/kg
Wheat	13.9	10^6 J/kg
Corn	8.6	10^6 J/kg
Beans	3.9	10^6 J/kg
Tubers	3.3	10^6 J/kg
Peanuts	24.6	10^6 J/kg
Rapeseeds	37.0	10^6 J/kg
Sesame	29.0	10^6 J/kg
Cotton and fiber crops	16.4	10^6 J/kg
Sugarcane and beetroots	5.0	10^6 J/kg
Tea and tobacco	10.7	10^6 J/kg
Silkworm cocoons	4.5	10^6 J/kg
Fruits	1.9	10^6 J/kg
Timber	8.0	10^6 J/kg
Meat	4.6	10^6 J/kg
Milk	4.9	10^6 J/kg
Poultry eggs	6.1	10^6 J/kg
Sheep wool, goat wool and cashmere	3.7	10^6J/kg
Aquatic products (seawater and freshwater)	5.8	10^6 J/kg
Copper	2.1	10^6 J/kg
Aluminum	32.9	10^6 J/kg
Zinc	5.4	10^6 J/kg
Ferrosilicon	22.8	10^6 J/kg
Steel	6.8	10^6J/kg
Phosphorite	0.1	10^6 J/kg
Crude salt	0.2	10^6J/kg
Nickel	4.3	10^6 J/kg
Magnesium	25.8	10^6 J/kg
Silicone	28.6	10^6 J/kg
FeSiMn	12.5	10^6 J/kg
Ferromanganese	10.3	10^6 J/kg
Ferrochrome	11.5	10^6 J/kg

values. The calculation of EE value is formulated as follows:

$$EE = CEC + E_C + E_W + E_R \tag{1}$$

where *CEC* represents the cumulative exergy consumption, i.e., the total exergy input into the product formation process, including the "raw material" exergy. Some cumulative exergy values used in this paper are listed in Table 1 [25,81,82]. E_C is the exergy equivalent of monetary flows, E_W is the exergy equivalent of human labor, and E_R stands for the environmental clean-up or remediation cost. In this study, we have computed the resource consumption of the remediation cost by converting into equivalent exergy the monetary investment on pollution removal, in the assumption that all the detected environmental impacts or deviations are compensated within the same year by human interventions, by means of investment of known monetary amounts.

The values of E_C and E_W are respectively calculated as

$$E_W = \alpha \times E_{in} \tag{2}$$

$$E_C = \beta \times E_w \tag{3}$$

The coefficients α and β describe the process and relationship with different parameters, where E_{in} is the exergy influx to the society.

As a measure of potential to cause environmental change, exergy may be, or provide the basis for, an effective measure of environmental impact, i.e., the potential of a substance or energy form to impact the environment. Alternative strategies to deal with the treatment of effluents can be formulated and assessed by using the EEA method. For this reason, in this paper the economic cost devoted on environmental remediation and management, as the environmental exergy consumption part, E_R, is calculated as

$$E_R = ee_K \times I_{env} \tag{4}$$

$$ee_K = \alpha \times \beta \times \frac{E_{in}}{M2} \tag{5}$$

where I_{env} is the monetary rate of investment in remediation measures, $M2$ is the monetary circulation, ee_K is the exergy equivalent for Capital. This is not exactly in line with the original EEA formulation, in which the environmental remediation cost is calculated on the basis of a – real or ideal – process in which the effluents are treated [83]. Such a calculation is clearly almost impossible for the present case, and our assumption must be viewed as an ad hoc approximation.

2.1.1. *The calculation expressions for α and β*

The calculation expressions for α and β were summarized as [82,84–88]:

$$\alpha = \frac{f \times e_{sure} \times N_h}{E_{in}} \tag{6}$$

$$\beta = \frac{M2}{s \times N_W \times W} \tag{7}$$

in which each parameter is illustrated in Table 2 as follows:

2.2. *Calculations*

2.2.1. *CEC accounting process*

Regarding Ex sector, the use of energy carriers to this part includes energy carriers (coal, coke, oil, petroleum productions, natural gas, and electricity), and the output includes coal, coke, oil, petroleum productions, natural gas and other minerals (iron, aluminum, copper, manganese, chromite, vanadium and so forth). For further explanation, the data of other minerals in this research mainly cover the largest output of metal and nonmetal parts and omits the trifle ones (see Table 1). For the Co sector, the inputs are the conventional fossil fuels produced from the Ex sector and the main outputs are electricity, including thermal power, nuclear power and hydropower from the environment, as well as heating (see Table 3). Ag sector is the fundamental industrial sector of China, from which the main inputs into the social system include five parts, i.e., farm products (wheat, rice, corn, beans, etc.), forest products (wood and bamboo), livestock products (meat, milk, wool and poultry eggs), aquatic products, biomass (biogas, straw and firewood), and water resources (see Table 3). However, a part of agricultural output is consumed by the Ag sector to sustain the agricultural system itself, e.g., some grains are used as feed to livestock breeding. To avoid double accounting, all these five parts indicate the net agricultural outputs that delivered to the social system. The most complicated one, In sector (mainly referring to the manufacturing industries), comprises textile industry, paper industry, iron and steel processing industry, nonferrous metal, nonmetal, chemical industry and other industries, contributing most to the consumption of fossil fuels, electricity, heat and the raw materials from the other sectors, and all the natural resource cumulative exergy consumption in this sector was calculated in Table 3. Tr sector presents the commercial storage, post, transportation services and services directly related to transportation (railways, highways, waterways, and civil aviation), of which the fossil energy consumption is mainly from Ex sector and electricity use from Co sector (see Table 3). With respect to Te sector, it is a collection of wholesale, retail, hotels, entertainment, catering and restaurant services, finance, real estate, construction and public services excluding transportation services. And the total invested exergy of energy in this sector is from the Ex and Co sectors

Table 2
The parameters used in the evaluation of α and β.

Parameter	Unit	Meaning
$f \times e_{sure}$	J/(person × day)	Exergy consumption amplification × exergy consumption for survival
N_h	–	Population
E_{in}	J/yr	Exergy influx input to the society
$M2$	RMB/yr	Money+Quasi-money circulation
S	RMB/yr	Average wage
N_W	–	Number of workers
W	Work-hours/(person × yr)	Average workload

Large portion of the $M2$ in China is time deposits and saving deposits, which is not the monetary circulation mode in accordance with those of the western bank system, and also checks cannot be freely cashed as it is in the western countries. Therefore, in this sense, we prefer GDP as the exergetic equivalent directly related to the production process to measure the monetary flux.
$f \times e_{sure}$ in this paper is 10^7 J/(person × day) according to previous research [3,84–86].

(see Table 3). In Do sector, the primary uses of exergy are coal, coke, petroleum products, natural gas, all of which were ultimately from the Ex sector. Electricity and heat were consumed which were obtained from Co sector; moreover, biogas energy used in this are mainly from Ag sector, all the above involved in accounting is displayed in Table 3. In order to make the research more comprehensive, we considered the input of biogas, straws and fuel wood, which is produced from Ag sector and consumed in Do sector especially common in rural areas in China.

Others in Ex sector (output) refer to 12 kinds of mineral, they are iron, aluminum, copper, manganese, chromite, vanadium, bauxite, magnesite ore, pyrite ore, potassium KCl, kaolin ore and Silicon materials.

In particular, water resource was included in the accounting process, which was usually excluded in the traditional classification of ecological resources based on the mainstream economics. Chemical exergy of water can be acquired by the exergy factors, but potential and phase transformation exergy cannot be calculated in the national scale at this moment due to the difficulty of statistic data and standard resulting in geographical difference as well as space–time complexity.

2.2.2. E_C accounting process

The capital contribution into sectors is regarded as the monetary input used to support social and economic circulations. Besides, as one consumptive end of the production chain, the Do sector was with zero capital production value. Only the labor was treated as the output of this sector, which was the difference between the Do-sector and the other sectors.

According to the accounting method presented, we collected the total data in the whole country by sector, which integrated the existed statistic yearbooks as well as internet databanks, and unified the classification of the seven sectors with other statistic process.

2.2.3. E_W accounting process

Labor can be considered as an output of Do sector, and input to all the other sectors. Work-hours is a unified standard for estimating different kinds of work in diverse population. In this research, we collected the population in employment classified in urban and rural areas. Considering that the farmers are not working full-time, we chose 0.5 as the coefficient [73], which multiplied by the population of Ag sector provides the actual number of rural workers; furthermore, 2000 h was chosen as the yearly workload in urban sectors. Similarly, the percentage of the working population in different sectors was used to allocate the available work-hours. Based on this accounting criterion, we collected data from CIESY, CMIN, CSY, CTY, NBSC and [89–93].

2.2.4. E_R accounting process

In EEA studies, there are two approaches used to calculate the environmental remediation cost, i.e., environmental investment based – [55] and cumulative exergy consumption based – accounting [94]. This paper applies EEA on sector level, a remediation process to neutralize the annual waste flows of a sector together cannot be designed. Furthermore, it was not possible to disaggregate the waste flows [79]. Thus, the cost based method was employed. In this paper we chose a less rigorous, but very effective, way to the internalization: first, compute the rate of investment in pollution-remediation, and then convert the monetary amount to primary resources using the EEA parameters. The rate of investment in pollution remediation for Ex, Co, and In can be found in environmental statistics [93], which provide a coefficient of environmental investment per GDP for industrial sectors. The environmental investment on Do and Te can also be found in [93]. For Tr sector, the emission coefficients and remediation costs in Dai et al. [95] are used. As no investment has been used for environmental remediation of Ag in China, the E_R of Ag is not calculated in this paper. This approximation ought to be corrected by future work on a more properly disaggregated database.

2.3. Equivalent exergy indicators of labor and capital

Two indicators, the labor production efficiency (LPE) and net input of resource exergy pro capite (IEPC), are proposed based on the EEA method to demonstrate the labor production efficiency as well as transfer ability from raw materials into monetary value. The mathematical formula can be presented as follows:

$$LPE(J/wh) = \frac{CEC}{Wh} \tag{8}$$

$$IEPC(J/USD) = \frac{CEC}{EcO} \tag{9}$$

where Wh represents the total work-hour input in resource exergy renovation and consumption process; EcO is economic output for exergy exploitation.

2.4. System diagram and data

The societal accounting initially proposed by Wall [21] focused on the cross-section from the resource base to end-use sectors: it followed indirectly the approach originally suggested by Szargut [96], and was improved by Ertesvåg [37] and Milia and Sciubba [77], who divided the society into seven subsystems interacting with their environment and labeling all fluxes of matter and energy in a metabolic-like process. Utlu and Hepbasli [30] also presented an illustration of the energy flows throughout the utility, natural resources, transportation, industrial, residential and commercial, and agricultural sectors. Later, Chen et al. [25] established a pyramidal scheme consisting of seven sectors, aiming to reveal the exergetic consumption structure of the society. In this study, we further modified the framework to show the extended exergetic structure of the society corresponding to the special socio-economic characteristics of the society.

In this research, the societal system was subdivided into the following sectors:

Ex: extraction, including mining and quarrying, oil and natural gas, refining and pre-processing.

Table 3
Exergy flow values of resource energy in seven sector, Unit: J.

Sector	Resource item	2000	2001	2002	2003	2004	2005	2006	2007
Ex sector (input)	**Coal**	2.47×10^{17}	1.54×10^{18}	2.14×10^{18}	2.84×10^{18}	2.55×10^{18}	3.19×10^{18}	3.47×10^{18}	3.68×10^{18}
	Petroleum	1.40×10^{18}	1.72×10^{18}	5.24×10^{18}	2.04×10^{18}	8.04×10^{17}	8.42×10^{17}	7.39×10^{17}	3.85×10^{16}
	Natural gas	3.73×10^{17}	3.94×10^{17}	4.09×10^{17}	4.16×10^{17}	3.94×10^{17}	4.50×10^{17}	4.45×10^{17}	4.92×10^{17}
	From Ex-sector	2.02×10^{18}	3.66×10^{18}	7.79×10^{18}	5.30×10^{18}	3.75×10^{18}	4.48×10^{18}	4.65×10^{18}	4.21×10^{18}
	Electricity	3.44×10^{17}	3.97×10^{17}	4.06×10^{17}	4.50×10^{17}	4.94×10^{17}	5.32×10^{17}	5.32×10^{17}	5.81×10^{17}
	From Co-sector	3.44×10^{17}	3.97×10^{17}	4.06×10^{17}	4.50×10^{17}	4.94×10^{17}	5.32×10^{17}	5.32×10^{17}	5.81×10^{17}
	Water	3.94×10^{16}	3.94×10^{16}	3.95×10^{16}	4.08×10^{16}	3.58×10^{16}	4.30×10^{16}	3.95×10^{16}	3.93×10^{16}
	Total	2.37×10^{18}	4.06×10^{18}	8.19×10^{18}	5.75×10^{18}	4.24×10^{18}	5.02×10^{18}	5.19×10^{18}	$4.80 \times \times 10^{18}$
Ex sector (output)	**Coal**	2.08×10^{19}	2.27×10^{19}	2.62×10^{19}	3.10×10^{19}	3.59×10^{19}	3.97×10^{19}	4.27×10^{19}	4.55×10^{19}
	Petroleum	6.91×10^{18}	6.99×10^{18}	7.16×10^{18}	7.27×10^{18}	7.47×10^{18}	$7.76 \times \times 10^{18}$	7.88×10^{18}	8.01×10^{18}
	Natural gas	1.10×10^{18}	1.23×10^{18}	1.32×10^{18}	1.42×10^{18}	1.68×10^{18}	1.99×10^{18}	$2.37 \times \times 10^{18}$	2.80×10^{18}
	Others	2.09×10^{17}	2.25×10^{17}	2.52×10^{17}	$2.88 \times \times 10^{17}$	3.27×10^{17}	3.59×10^{17}	3.85×10^{17}	4.09×10^{17}
	Total	2.90×10^{19}	3.12×10^{19}	3.49×10^{19}	4.00×10^{19}	4.53×10^{19}	4.98×10^{19}	5.33×10^{19}	5.67×10^{19}
Co sector (electricity production)	**Hydropower**	$8.01 \times \times 10^{17}$	9.99×10^{17}	1.04×10^{18}	1.02×10^{18}	1.27×10^{18}	1.43×10^{18}	1.57×10^{18}	1.75×10^{18}
	Thermal power	4.01×10^{18}	4.24×10^{18}	4.78×10^{18}	5.69×10^{18}	6.46×10^{18}	7.37×10^{18}	8.53×10^{18}	9.80×10^{18}
	Nuclear power	6.02×10^{16}	$6.29 \times \times 10^{16}$	9.04×10^{16}	1.56×10^{17}	1.82×10^{17}	1.91×10^{17}	1.97×10^{17}	2.24×10^{17}
	Imported	5.55×10^{15}	$6.47 \times \times 10^{15}$	8.26×10^{15}	1.07×10^{16}	1.22×10^{16}	1.80×10^{16}	1.94×10^{16}	1.53×10^{16}
	Exported	3.57×10^{16}	3.68×10^{16}	3.50×10^{16}	3.73×10^{16}	3.42×10^{16}	4.04×10^{16}	4.43×10^{16}	5.26×10^{16}
	Total	4.91×10^{18}	5.34×10^{18}	5.95×10^{18}	6.91×10^{18}	7.96×10^{18}	$9.05 \times \times 10^{18}$	1.04×10^{19}	1.18×10^{19}
Co sector (heat conversion)	**Coal**	1.57×10^{19}	1.62×10^{19}	1.74×10^{19}	1.87×10^{19}	2.13×10^{19}	2.59×10^{19}	3.87×10^{19}	$4.25 \times \times 10^{19}$
	Petroleum	5.73×10^{17}	5.26×10^{17}	6.67×10^{17}	8.08×10^{17}	$9.71 \times \times 10^{17}$	9.11×10^{17}	8.38×10^{17}	8.37×10^{17}
	Other	1.46×10^{18}	1.50×10^{18}	1.62×10^{18}	1.74×10^{18}	2.00×10^{18}	2.40×10^{18}	3.54×10^{18}	3.88×10^{18}
	Total	$1.77 \times \times 10^{19}$	1.83×10^{19}	1.97×10^{19}	2.12×10^{19}	2.43×10^{19}	2.92×10^{19}	4.31×10^{19}	4.72×10^{19}
Ag sector (input)	**Coal**	3.98×10^{17}	3.95×10^{17}	3.92×10^{17}	4.05×10^{17}	5.22×10^{17}	5.28×10^{17}	5.30×10^{17}	6.11×10^{19}
	Petroleum	1.71×10^{18}	1.70×10^{18}	1.70×10^{18}	7.58×10^{17}	9.00×10^{17}	9.32×10^{17}	9.95×10^{17}	1.75×10^{19}
	From Ex-sector	2.11×10^{18}	2.10×10^{18}	2.09×10^{18}	1.16×10^{18}	1.42×10^{18}	1.46×10^{18}	1.53×10^{18}	7.86×10^{19}
	Electricity	2.42×10^{17}	2.61×10^{17}	2.79×10^{17}	2.78×10^{17}	2.91×10^{17}	3.15×10^{17}	3.41×10^{17}	3.52×10^{17}
	From Co-sector	2.42×10^{17}	2.61×10^{17}	2.79×10^{17}	2.78×10^{17}	2.91×10^{17}	3.15×10^{17}	3.41×10^{17}	3.52×10^{17}
	Water	1.89×10^{18}	1.91×10^{18}	1.87×10^{18}	1.72×10^{18}	1.51×10^{18}	1.73×10^{18}	1.56×10^{18}	1.55×10^{18}
	Total	4.24×10^{18}	4.27×10^{18}	4.24×10^{18}	$3.16 \times \times 10^{18}$	3.22×10^{18}	3.51×10^{18}	3.43×10^{18}	8.05×10^{19}
Ag sector (output)	**Rice**	2.97×10^{18}	2.81×10^{18}	2.76×10^{18}	2.54×10^{18}	2.83×10^{18}	2.85×10^{18}	2.87×10^{18}	2.94×10^{18}
	Wheat	1.38×10^{18}	1.30×10^{18}	1.25×10^{18}	$1.20 \times \times 10^{18}$	1.28×10^{18}	1.35×10^{18}	$1.51 \times \times 10^{18}$	1.52×10^{18}
	Corn	9.12×10^{17}	9.81×10^{17}	1.04×10^{18}	9.96×10^{17}	1.12×10^{18}	1.20×10^{18}	1.30×10^{18}	1.31×10^{18}
	Beans	7.85×10^{16}	8.02×10^{16}	$8.76 \times \times 10^{16}$	8.31×10^{16}	8.72×10^{16}	8.43×10^{16}	7.83×10^{16}	6.72×10^{16}
	Tubers	1.56×10^{17}	1.51×10^{17}	1.55×10^{17}	1.49×10^{17}	1.51×10^{17}	1.47×10^{17}	1.15×10^{17}	1.19×10^{17}
	Peanut	3.54×10^{17}	3.54×10^{17}	3.63×10^{17}	3.29×10^{17}	3.52×10^{17}	3.52×10^{17}	3.16×10^{17}	3.19×10^{17}
	Rapeseeds	4.23×10^{17}	4.21×10^{17}	$3.92 \times \times 10^{17}$	4.24×10^{17}	4.90×10^{17}	4.85×10^{17}	4.07×10^{17}	3.93×10^{17}
	Sesame	2.26×10^{16}	2.24×10^{16}	2.49×10^{16}	1.65×10^{16}	1.96×10^{16}	1.74×10^{16}	1.84×10^{16}	1.55×10^{16}
	Fiber crops	7.23×10^{16}	8.71×10^{16}	8.04×10^{16}	7.95×10^{16}	1.03×10^{17}	9.35×10^{16}	1.23×10^{17}	1.25×10^{17}
	Hemp	8.63×10^{15}	1.11×10^{16}	1.57×10^{16}	1.39×10^{16}	1.75×10^{16}	1.80×10^{16}	1.45×10^{16}	1.19×10^{16}
	Sugar crops	3.82×10^{17}	4.33×10^{17}	5.15×10^{17}	4.82×10^{17}	4.78×10^{17}	4.73×10^{17}	5.23×10^{17}	6.09×10^{17}
	Silkworm Cocoons	2.53×10^{15}	3.02×10^{15}	3.22×10^{15}	3.08×10^{15}	3.37×10^{15}	3.60×10^{15}	4.07×10^{15}	4.37×10^{15}
	Tea and tobacco	3.44×10^{16}	3.25×10^{15}	3.40×10^{15}	3.22×10^{15}	3.45×10^{15}	3.85×10^{15}	3.71×10^{15}	3.79×10^{15}
	Vegetable	$9.25 \times \times 10^{17}$	9.62×10^{17}	9.99×10^{17}	1.04×10^{18}	1.07×10^{18}	1.07×10^{18}	1.04×10^{18}	1.07×10^{18}
	Fruits	5.34×10^{16}	5.71×10^{16}	5.96×10^{16}	1.25×10^{17}	1.32×10^{17}	1.38×10^{17}	1.47×10^{17}	1.56×10^{17}
	Total farm products	7.78×10^{18}	7.71×10^{18}	7.79×10^{18}	7.51×10^{18}	8.17×10^{18}	8.33×10^{18}	8.50×10^{18}	8.69×10^{18}
	Wood	3.78×10^{17}	3.64×10^{17}	3.55×10^{17}	3.81×10^{17}	4.16×10^{17}	4.45×10^{17}	5.29×10^{17}	5.58×10^{17}
	Bamboo	2.43×10^{17}	2.34×10^{17}	2.28×10^{17}	2.45×10^{17}	2.68×10^{17}	2.86×10^{17}	3.41×10^{17}	3.59×10^{17}
	Total forest products	$6.2 \times 1 \times 10^{17}$	5.99×10^{17}	5.83×10^{17}	6.26×10^{17}	6.83×10^{17}	7.31×10^{17}	8.69×10^{17}	$9.17 \times v10^{17}$
	Meat	$1.22 \times \times 10^{18}$	1.24×10^{18}	1.26×10^{18}	1.31×10^{18}	1.34×10^{18}	1.41×10^{18}	1.44×10^{18}	1.39×10^{18}
	Milk	4.32×10^{16}	5.28×10^{16}	6.59×10^{16}	8.70×10^{16}	1.11×10^{17}	1.35×10^{17}	1.55×10^{17}	1.71×10^{17}

	Wool	1.13×10^{15}	1.16×10^{15}	1.19×10^{15}	1.31×10^{15}	1.43×10^{15}	1.50×10^{15}	1.50×10^{15}	1.42×10^{15}
	Poultry eggs	1.60×10^{17}	1.62×10^{17}	1.66×10^{17}	1.71×10^{17}	1.74×10^{17}	1.79×10^{17}	1.78×10^{17}	1.86×10^{17}
	Total livestock products	1.42×10^{18}	1.45×10^{18}	1.50×10^{18}	1.57×10^{18}	1.63×10^{18}	1.72×10^{18}	1.77×10^{18}	1.75×10^{18}
	Aquatic products	2.48×10^{17}	2.54×10^{17}	2.65×10^{17}	2.73×10^{17}	2.84×10^{17}	2.96×10^{17}	3.07×10^{17}	3.18×10^{17}
	Biogas	4.20×10^{16}	4.39×10^{16}	4.60×10^{16}	8.55×10^{16}	1.03×10^{17}	1.28×10^{17}	1.55×10^{17}	1.89×10^{17}
	Straws	3.80×10^{18}	4.28×10^{18}	4.28×10^{18}	4.39×10^{18}	4.48×10^{18}	4.91×10^{18}	4.99×10^{18}	4.48×10^{18}
	Fuel wood	2.35×10^{18}	2.57×10^{18}	2.57×10^{18}	3.40×10^{18}	3.52×10^{18}	3.01×10^{18}	3.17×10^{18}	3.04×10^{18}
	Total biomass	6.19×10^{18}	6.89×10^{18}	6.90×10^{18}	7.87×10^{18}	8.10×10^{18}	8.04×10^{18}	8.31×10^{18}	7.71×10^{18}
	Total	1.63×10^{19}	1.69×10^{19}	1.70×10^{19}	1.79×10^{19}	1.89×10^{19}	1.91×10^{19}	1.98×10^{19}	1.94×10^{19}
In sector (consumption)	**Coal**	9.16×10^{18}	1.09×10^{19}	1.27×10^{19}	1.45×10^{19}	1.74×10^{19}	1.98×10^{19}	2.23×10^{19}	2.43×10^{19}
	Petroleum products	1.71×10^{18}	1.85×10^{18}	1.98×10^{18}	2.12×10^{18}	2.42×10^{18}	2.47×10^{18}	2.61×10^{18}	2.70×10^{18}
	Natural gas	4.80×10^{17}	5.42×10^{17}	6.04×10^{17}	6.67×10^{17}	7.31×10^{17}	8.81×10^{17}	1.03×10^{18}	1.27×10^{18}
	From Ex-sector	1.14×10^{19}	1.33×10^{19}	1.53×10^{19}	1.73×10^{19}	2.05×10^{19}	2.31×10^{19}	2.59×10^{19}	2.82×10^{19}
	Electricity	2.10×10^{18}	2.51×10^{18}	2.93×10^{18}	3.34×10^{18}	3.91×10^{18}	4.44×10^{18}	5.11×10^{18}	5.92×10^{18}
	Heat	1.64×10^{17}	1.93×10^{17}	2.23×10^{17}	2.52×10^{17}	2.98×10^{17}	3.37×10^{17}	3.79×10^{17}	4.17×10^{17}
	From Co-sector	2.26×10^{18}	2.70×10^{18}	3.15×10^{18}	3.59×10^{18}	4.20×10^{18}	4.78×10^{18}	5.49×10^{18}	6.34×10^{18}
	Water	4.67×10^{17}	4.68×10^{17}	4.68×10^{17}	4.85×10^{17}	4.25×10^{17}	5.10×10^{17}	4.68×10^{17}	4.67×10^{17}
	Total	1.41×10^{19}	1.65×10^{19}	1.89×10^{19}	2.14×10^{19}	2.51×10^{19}	2.84×10^{19}	3.19×10^{19}	3.50×10^{19}
Tr sector (consumption)	**Coal**	2.51×10^{17}	2.36×10^{17}	2.34×10^{17}	2.37×10^{17}	1.85×10^{17}	1.81×10^{17}	1.61×10^{17}	1.52×10^{17}
	Petroleum products	2.48×10^{18}	2.56×10^{18}	2.78×10^{18}	3.20×10^{18}	3.89×10^{18}	4.38×10^{18}	4.94×10^{18}	5.54×10^{18}
	Natural gas	2.97×10^{16}	3.05×10^{16}	3.26×10^{16}	3.49×10^{16}	5.70×10^{16}	6.65×10^{16}	8.81×10^{16}	8.63×10^{16}
	From Ex-sector	2.76×10^{18}	2.82×10^{18}	3.04×10^{18}	3.47×10^{18}	4.13×10^{18}	4.62×10^{18}	5.19×10^{18}	5.78×10^{18}
	Electricity	1.01×10^{17}	1.11×10^{17}	1.22×10^{17}	1.43×10^{17}	1.62×10^{17}	1.55×10^{17}	1.68×10^{17}	1.91×10^{17}
	From Co-sector	1.01×10^{17}	1.11×10^{17}	1.22×10^{17}	1.43×10^{17}	1.62×10^{17}	1.55×10^{17}	1.68×10^{17}	1.91×10^{17}
	Total	2.87×10^{18}	2.94×10^{18}	3.16×10^{18}	3.61×10^{18}	4.29×10^{18}	4.78×10^{18}	5.36×10^{18}	5.97×10^{18}
Te sector (consumption)	**Coal**	4.89×10^{17}	4.87×10^{17}	5.17×10^{17}	5.17×10^{17}	5.23×10^{17}	5.25×10^{17}	5.35×10^{17}	5.21×10^{17}
	Petroleum products	9.29×10^{17}	8.64×10^{17}	1.16×10^{18}	1.16×10^{18}	1.39×10^{18}	1.56×10^{18}	1.69×10^{18}	1.90×10^{18}
	Natural gas	6.09×10^{15}	3.81×10^{16}	7.58×10^{16}	7.58×10^{16}	1.02×10^{17}	1.19×10^{17}	1.46×10^{17}	$1.89\times\times10^{17}$
	From Ex-sector	1.42×10^{18}	1.39×10^{18}	1.75×10^{18}	1.75×10^{18}	2.02×10^{18}	2.20×10^{18}	2.37×10^{18}	2.61×10^{18}
	Electricity	4.38×10^{17}	4.95×10^{17}	6.94×10^{17}	6.94×10^{17}	8.19×10^{17}	8.38×10^{17}	9.44×10^{17}	1.04×10^{18}
	From Co-sector	4.38×10^{17}	4.95×10^{17}	6.94×10^{17}	6.94×10^{17}	8.19×10^{17}	8.38×10^{17}	9.44×10^{17}	1.04×10^{18}
	Water	1.32×10^{16}	1.32×10^{16}	1.32×10^{16}	1.36×10^{16}	1.20×10^{16}	1.44×10^{16}	1.32×10^{16}	1.31×10^{16}
	Total	1.87×10^{18}	1.89×10^{18}	2.46×10^{18}	$2.46\times\times10^{18}$	2.85×10^{18}	3.05×10^{18}	3.33×10^{18}	$3.66\times\times10^{18}$
Do sector (consumption)	**Coal**	1.78×10^{18}	1.76×10^{18}	1.71×10^{18}	1.84×10^{18}	1.84×10^{18}	1.97×10^{18}	1.89×10^{18}	1.82×10^{18}
	Petroleum products	6.36×10^{17}	6.49×10^{17}	7.38×10^{17}	8.09×10^{17}	8.27×10^{17}	8.13×10^{17}	8.87×10^{17}	9.76×10^{17}
	Natural gas	1.74×10^{17}	2.34×10^{17}	2.52×10^{17}	2.69×10^{17}	2.94×10^{17}	3.22×10^{17}	3.71×10^{17}	4.21×10^{17}
	From Ex-sector	2.59×10^{18}	2.65×10^{18}	2.70×10^{18}	2.92×10^{18}	2.96×10^{18}	3.10×10^{18}	3.15×10^{18}	3.22×10^{18}
	Heat	2.32×10^{17}	2.34×10^{17}	2.66×10^{17}	3.37×10^{17}	4.14×10^{17}	5.17×10^{17}	5.69×10^{17}	5.77×10^{17}
	Electricity	6.02×10^{17}	6.62×10^{17}	7.20×10^{17}	8.06×10^{17}	8.87×10^{17}	1.02×10^{18}	1.17×10^{18}	1.30×10^{18}
	From Co-sector	8.34×10^{17}	8.96×10^{17}	9.87×10^{17}	1.14×10^{18}	1.30×10^{18}	1.53×10^{18}	1.74×10^{18}	1.88×10^{18}
	Biogas	4.20×10^{16}	4.39×10^{16}	4.60×10^{16}	8.55×10^{16}	1.03×10^{17}	1.28×10^{17}	1.55×10^{17}	1.89×10^{17}
	Straws	3.80×10^{18}	4.28×10^{18}	4.28×10^{18}	4.39×10^{18}	4.48×10^{18}	4.91×10^{18}	4.99×10^{18}	4.48×10^{18}
	Fuel wood	2.35×10^{18}	2.57×10^{18}	2.57×10^{18}	3.40×10^{18}	3.52×10^{18}	3.01×10^{18}	3.17×10^{18}	3.04×10^{18}
	From Ag-sector	6.19×10^{18}	6.89×10^{18}	6.90×10^{18}	7.87×10^{18}	8.10×10^{18}	8.04×10^{18}	8.31×10^{18}	7.71×10^{18}
	Water	2.87×10^{17}	3.00×10^{17}	3.09×10^{17}	3.17×10^{17}	2.75×10^{17}	3.27×10^{17}	2.95×10^{17}	2.94×10^{17}
	Total	9.91×10^{18}	1.07×10^{19}	1.09×10^{19}	1.22×10^{19}	1.27×10^{19}	1.30×10^{19}	1.35×10^{19}	1.31×10^{19}

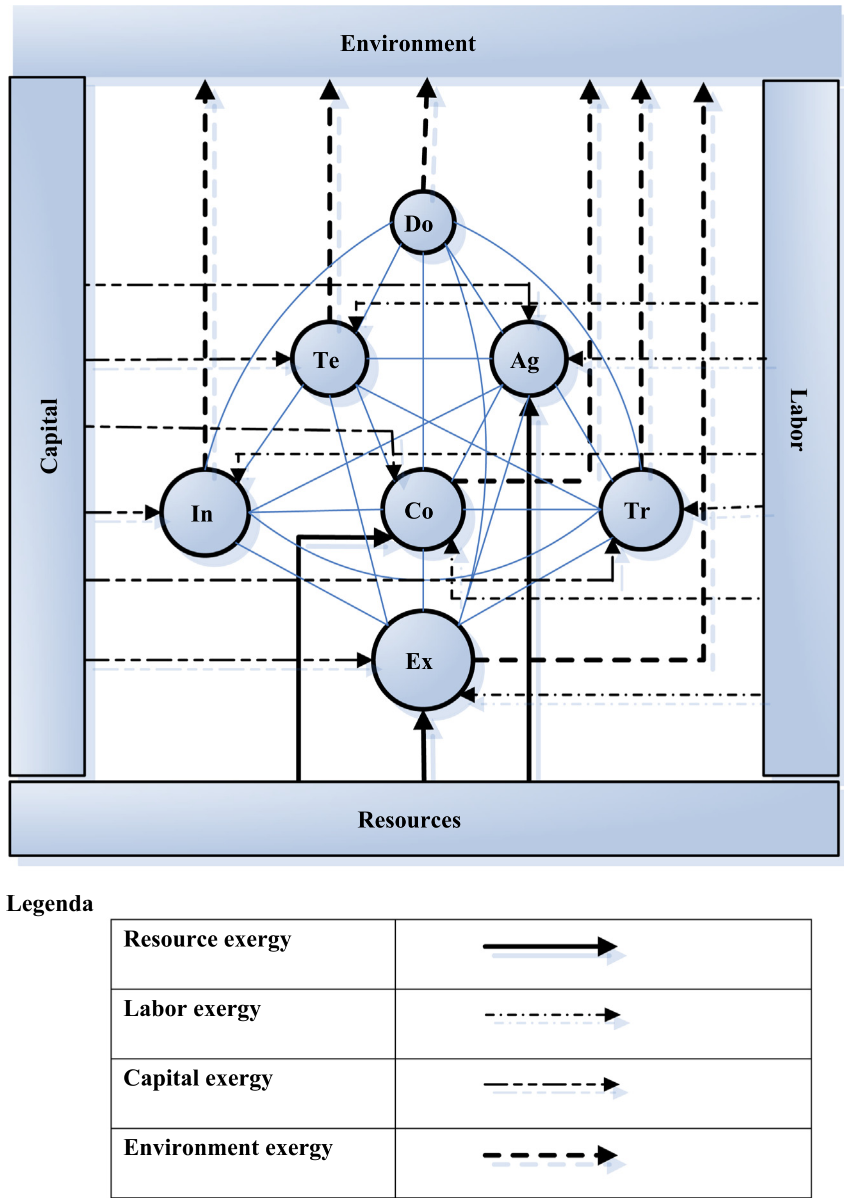

Fig. 2. System diagram for extended-exergy/USD resource accounting.

Co: conversion of primary energy & materials into heat, power and electricity.
Ag: harvesting, forestry, animal husbandry, fishery, water cultures, and food processing.
In: industry, manufacturing industry except oil refineries.
Tr: transportation services.
Te: tertiary, including construction and real estate.
Do: domestic sector, households.

The sectoral classification, pioneered by Wall [21] and later followed and improved by Szargut [96], Ertesvåg [37], and Milia and Sciubba [77], was based on the cross-section of societal accounting. It has also been presented in the Chinese social system by Cai [97], Cai et al. [26], Chen and Qi [82], and Zhang and Chen [98].

In Fig. 2, the black broken line-pane is the boundary of the society system. “Resource” means the energy and materials extracted from the natural environment, while “Environment” here refers to the surrounding part of the society system as a “dump” of waste emissions. Each sector was represented by a circle with area proportional to its extended exergy content including exergy, labor, capital and environmental remediation cost (all made dimensionless by dividing them by those for the Domestic Sector). The input of resources and output of products are shown by solid lines, waste emissions by dashed lines, labor by dash-dot lines and capital by dash double-dot lines. Each line corresponds to the cumulative extended exergy in–out resource exergy flow exchanges among the system, abroad and environment. The hierarchical structure is then established according to both the values of the ratio of extended exergy content to production value/income and the distribution of sectors composing the value-adding chain from natural environment to the domestic sector, thereby forming a seemingly pyramid-type structure, constructed on the basis of the value of extended exergy consumption pro capita acquired in Section 3. The detailed values are to be listed in the part of Sections 3 and 4.

The data of the current study were collected from the standard yearbooks compiled by the central government and its subordinate ministries. Detailed data for individual sectors can be referred

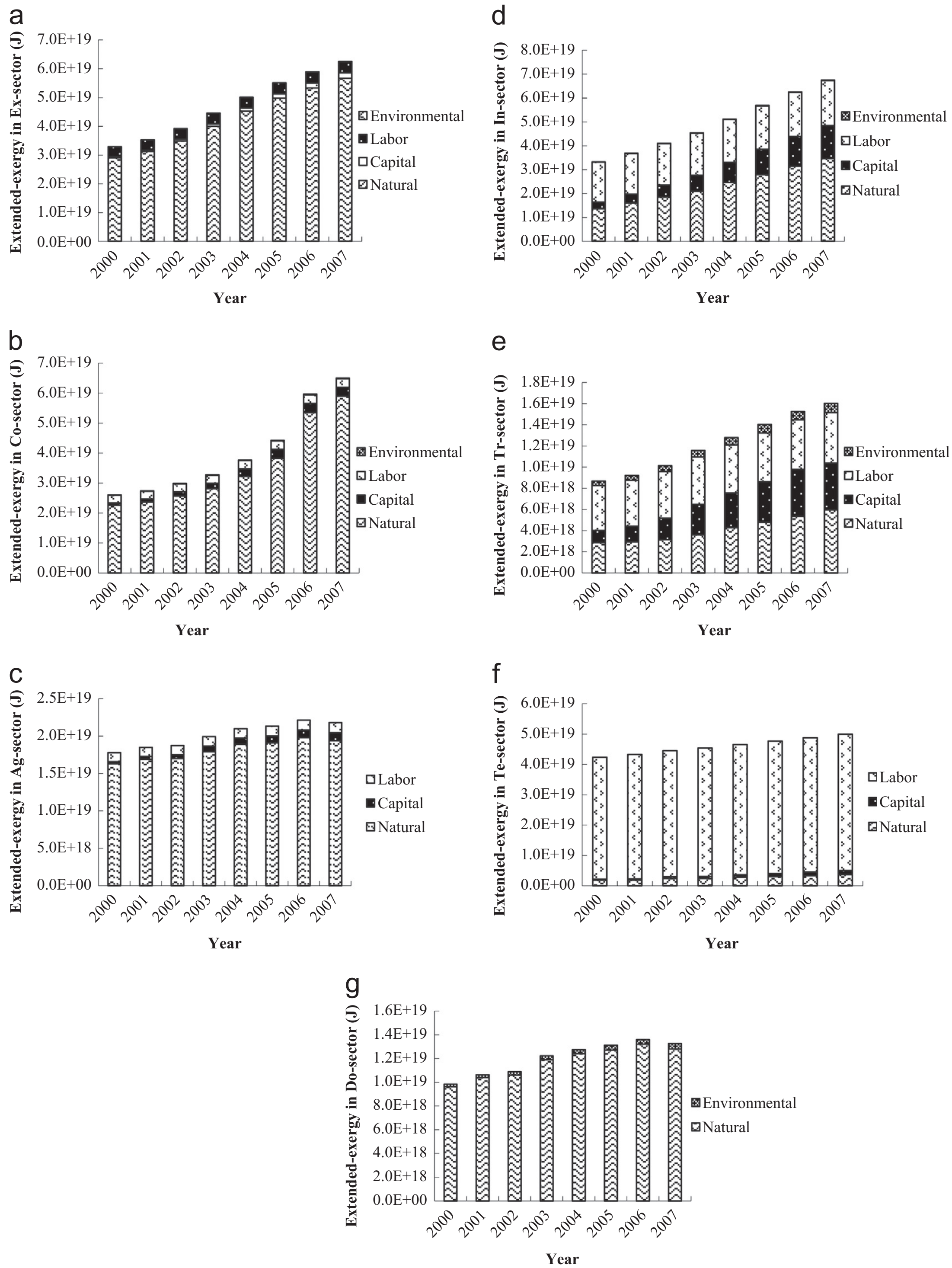

Fig. 3. (a). Inter-annual variation of extended exergy in Ex sector; (b). Inter-annual variation of extended exergy in Co sector; (c). Inter-annual variation of extended exergy in Ag sector; (d). Inter-annual variation of extended exergy in In sector; (e). Inter-annual variation of extended exergy in Tr sector; (f). Inter-annual variation of extended exergy in Te sector; and (g). Inter-annual variation of extended exergy in Do sector.

to the ministry yearbooks (2001–2008), e.g., CAY, CFIN, CFSY, CSY [89,99–101] for Ag sector; CESY, CFESY, CSY [89,102,103] for most sectors; CISIY, CNMY, [104,105] for In sector; CMY, CSY [89,106] for Ex sector; and CTY, CSY [89,92] for Tr sector. Some were from the network database, including, NBSC, PBC, IBE and CMIN [92,93,107,108]. In China Statistical Yearbooks, both the conversion (Co) and extraction (Ex) were included within the industry sector: in this study, they were though considered as independent sectors external to the industry sector in that these two sectors were usually responsible for the major portion of the flows of exergy into and out of the E (environment).

3. Results

The inter-annual variation of extended exergy in seven sectors is shown in Fig. 3. The yearly values of resource exergy in seven

Table 4a
The capital data in seven sectors from 2000 to 2007, Unit:108 RMB.

C	2000	2001	2002	× 2003	2004	2005	2006	2007
C-Ex	675.76	922.10	1287.90	1775.19	2395.85	3587.35	4678.40	5878.81
C-Ag	563.13	768.42	1073.25	1652.30	1890.70	2323.66	2749.94	3403.50
C-Co	1576.76	2151.58	3005.10	3962.40	5795.13	7554.42	8585.67	9467.58
C-In	5631.30	7684.20	10732.50	14689.53	19585.49	26575.97	34089.51	44505.13
C-Tr	2252.52	3073.68	4293.00	6289.38	7646.23	9614.03	12138.12	14154.01
C-Te	563.13	768.42	1073.25	1345.71	1833.75	2525.15	3361.03	4399.75
C-Total capital	11262.60	15368.40	21465.00	29714.51	39147.15	52180.58	65602.67	81808.77
GDP	98000.45	108068.22	119095.69	135173.98	159586.75	184088.60	213131.70	259258.90

Table 4b
The work-hours of whole social labor in 2000–2007, Unit: work-hours.

	2000	2001	2002	2003	2004	2005	2006	2007
Urban work-hours	4.63×10^{11}	4.79×10^{11}	4.96×10^{11}	5.13×10^{11}	5.30×10^{11}	5.47×10^{11}	5.66×10^{11}	5.87×10^{11}
Rural work-hours	4.89×10^{11}	4.91×10^{11}	4.90×10^{11}	4.88×10^{11}	4.87×10^{11}	4.85×10^{11}	4.81×10^{11}	4.76×10^{11}
Total hours	9.52×10^{11}	9.70×10^{11}	9.85×10^{11}	1.00×10^{12}	1.02×10^{12}	1.03×10^{12}	1.05×10^{12}	1.06×10^{12}

sectors are reported in Table 3, with the extended exergy values in Table 5 computed on the basis of the information contained in Tables 4a and 4b.

3.1. Structural transformation of extended exergy in whole society

Table 6 shows the variation of the four extended exergy constituents (natural, labor-equivalent, capital-equivalent and environmental remediation-equivalent resources) in China from 2000 to 2007. The results indicate that the 8 years saw a steady rise in total extended exergy, which were the combined effects of the effects of four elements. Firstly, natural exergy input into the eco-social system had increased from 4.94×10^{19} J in 2000 to 8.11×10^{19} J in 2007, an increase of about 164%. Secondly, the value of capital exergy was augmented 4.5 times the value in 2000. In addition, labor and environmental exergy had risen steadily but slowly during this study period. China is a populous nation with an abundant labor force, which leads to a labor-extensive industrial structure. In the long run, a more productive and competitive social mode should be constructed, which depends on high technology input as well as financial administration and utilization, rather than on consumption of manpower primarily. In the result reported in this paper, a slow rise in the labor component implied relatively stable industrial structure and technical level, and a position in a transition period from extensive into intensive economy, considering the greater level of resource use and money circulation, with less work.

In conclusion, resource level as well as currency contributions to social and economic development have played an important role in the present phase in China, with a large amount of labor as an advantageous factor, which will not weaken in short time. Moreover, more attention should be paid to environmental remediation in future planning, viewed as a long-term task, and implemented not only by governments, but also by corporations and specific departments.

3.2. Inter-annual variation of extended exergy in seven sectors

Generally speaking, the input of energy carriers to the Ex sector includes three kinds of traditional fossil fuels (coal, petroleum and natural gas), and 12 other main kinds of minerals (such as, iron, manganese, chromite, vanadium and so on). Coke and electricity are expected in the calculation process because they are man-made secondary energy resources, which are not extracted from the environment in usable form directly. For the Co sector, the main outputs of the conversion part are electricity and district heat, which are partly obtained from natural resource input (hydropower, thermal power, and nuclear power) and partly produced from Ex sector. The Ag sector is a basic and important industry in China, and the main input from the Ag sector into the social system consists of five parts, categorized here as 22 kinds of Ag food. These include 15 kinds of farm products, 2 kinds of forest products (wood and bamboo), 5 kinds of livestock products, and aquatic products. The In sector (mainly referring to the manufacturing industries) comprises subsystems that include textile industry, paper industry, iron and steel processing industry, non-ferrous metal, non-metal, and chemical industry. The consumed resources consist mainly of fossil fuel energy as well as electricity and heat. The Tr sector presented the commercial transportation services and services directly related to transportation, and the data for this sector contain consumed fossil energy mainly from Ex sector and electricity used mainly from Co sector. The Te sector is an integration of wholesale, retail, hotels, entertainment, restaurant, finance, real estate, construction and public services, which include governments, hospitals, schools, but excludes transportation services. The total invested exergy of energy in this sector is from the Ex sector. In the Do sector, the use of exergy is primarily from coal, coke, petroleum products, natural gas, all of which were ultimately derived from the Ex sector. Moreover, electricity and heat consumed were obtained from the Co sector. As mentioned in the *CEC* accounting process, we also considered the input of biogas, straws and fuel wood in this research.

The yearly diversification in different seven sectors during 2000–2007 is shown in Fig. 3. In the Ex, Co and Ag sectors (see Fig. 3a–c), natural resource exergy input was the most dominant exergy carrier, in which Ex and Co sectors had an increasing tendency, with percentage varied from 88.2% to 90.7% and 86.7% to 90.7%, respectively. Ag sector, one of the three departments directly and mainly dependent on natural support, exhibited a gradually falling trend in *CEC* proportion from 91.7% down to 89.0%. The role of E_C in all three sectors, Ex, Co and Ag, strengthened to values of 1.8×10^{18} J, 3.0×10^{18} J, 1.1×10^{18} J in 2007, respectively. Meanwhile, the percentage of E_W in Ex and Co sectors both declined, which indicated labor's contribution was not as important as it was in the past years, as capital inputs, technical improvements and mechanical devotions on productiveness were taking the place of manpower. It should be noted that, environmental remediation ausgeben in Ex, Co sectors were insignificant

Table 5
The extended exergy accounting in seven sectors from 2000 to 2007, Unit: J.

Extended exergy item	Sector	2000	2001	2002	2003	2004	2005	2006	2007
Capital exergy	**Ex**	3.41×10^{17}	4.46×10^{17}	6.08×10^{17}	8.14×10^{17}	1.03×10^{18}	1.44×10^{18}	1.71×10^{18}	1.84×10^{18}
	Co	7.95×10^{17}	1.04×10^{18}	1.42×10^{18}	1.82×10^{18}	2.49×10^{18}	3.03×10^{18}	3.14×10^{18}	2.96×10^{18}
	Ag	2.84×10^{17}	3.72×10^{17}	5.06×10^{17}	7.58×10^{17}	8.12×10^{17}	9.32×10^{17}	1.01×10^{18}	1.06×10^{18}
	In	2.84×10^{18}	3.72×10^{18}	5.06×10^{18}	6.74×10^{18}	8.41×10^{18}	1.07×10^{19}	1.25×10^{19}	1.39×10^{19}
	Tr	1.14×10^{18}	1.49×10^{18}	2.03×10^{18}	2.88×10^{18}	3.28×10^{18}	3.85×10^{18}	4.44×10^{18}	4.43×10^{18}
	Te	2.84×10^{17}	3.72×10^{17}	5.06×10^{17}	6.17×10^{17}	7.87×10^{17}	1.01×10^{18}	1.23×10^{18}	1.38×10^{18}
	Do	0	0	0	0	0	0	0	0
	Total	5.68×10^{18}	7.44×10^{18}	1.01×10^{19}	1.36×10^{19}	1.68×10^{19}	2.09×10^{19}	2.40×10^{19}	2.56×10^{19}
Labor exergy	**Ex**	3.53×10^{18}	3.59×10^{18}	3.65×10^{18}	3.71×10^{18}	3.76×10^{18}	3.82×10^{18}	3.88×10^{18}	3.94×10^{18}
	Co	2.55×10^{18}	2.60×10^{18}	2.64×10^{18}	2.68×10^{18}	2.73×10^{18}	2.77×10^{18}	2.81×10^{18}	2.85×10^{18}
	Ag	1.20×10^{18}	1.22×10^{18}	1.24×10^{18}	1.26×10^{18}	1.28×10^{18}	1.30×10^{18}	1.32×10^{18}	1.34×10^{18}
	In	1.67×10^{19}	1.70×10^{19}	1.73×10^{19}	1.76×10^{19}	1.79×10^{19}	1.81×10^{19}	1.84×10^{19}	1.87×10^{19}
	Tr	4.25×10^{18}	4.33×10^{18}	4.40×10^{18}	4.47×10^{18}	4.54×10^{18}	4.61×10^{18}	4.68×10^{18}	4.75×10^{18}
	Te	4.02×10^{19}	4.10×10^{19}	4.16×10^{19}	4.23×10^{19}	4.29×10^{19}	4.36×10^{19}	4.42×10^{19}	4.49×10^{19}
	Do	0	0	0	0	0	0	0	0
	Total	6.85×10^{19}	6.97×10^{19}	7.08×10^{19}	7.20×10^{19}	7.31×10^{19}	7.42×10^{19}	7.53×10^{19}	7.65×10^{19}
Environmental exergy	**Ex**	1.67×10^{16}	1.75×10^{16}	2.11×10^{16}	2.44×10^{16}	2.68×10^{16}	3.13×10^{16}	3.07×10^{16}	3.46×10^{16}
	Co	1.23×10^{17}	1.29×10^{17}	1.55×10^{17}	1.80×10^{17}	1.97×10^{17}	2.31×10^{17}	2.26×10^{17}	2.55×10^{17}
	Ag	0	0	0	0	0	0	0	0
	In	1.10×10^{17}	1.15×10^{17}	1.39×10^{17}	1.61×10^{17}	1.76×10^{17}	2.06×10^{17}	2.02×10^{17}	2.28×10^{17}
	Tr	4.29×10^{17}	4.49×10^{17}	5.41×10^{17}	6.26×10^{17}	6.88×10^{17}	8.03×10^{17}	7.88×10^{17}	8.89×10^{17}
	Te	0	0	0	0	0	0	0	0
	Do	2.19×10^{17}	2.29×10^{17}	2.76×10^{17}	3.19×10^{17}	3.51×10^{17}	4.09×10^{17}	4.02×10^{17}	4.53×10^{17}
	Total	9.00×10^{17}	9.42×10^{17}	1.13×10^{18}	1.31×10^{18}	1.44×10^{18}	1.68×10^{18}	1.65×10^{18}	1.86×10^{18}

Table 6
Extended exergy constitution in China from 2000 to 2007, Unit: J.

	2000	2001	2002	2003	2004	2005	2006	2007
Total natural exergy	4.94×10^{19}	5.23×10^{19}	5.62×10^{19}	6.20×10^{19}	6.85×10^{19}	7.38×10^{19}	7.80×10^{19}	8.11×10^{19}
Capital exergy	5.68×10^{18}	7.44×10^{18}	1.01×10^{19}	1.36×10^{19}	1.68×10^{19}	2.09×10^{19}	2.40×10^{19}	2.56×10^{19}
Labor exergy	6.85×10^{19}	6.97×10^{19}	7.08×10^{19}	7.20×10^{19}	7.31×10^{19}	7.42×10^{19}	7.53×10^{19}	7.65×10^{19}
Environmental exergy	9.00×10^{17}	9.42×10^{17}	1.13×10^{18}	1.31×10^{18}	1.44×10^{18}	1.68×10^{18}	1.65×10^{18}	1.86×10^{18}
Total extended exergy	1.24×10^{20}	1.30×10^{20}	1.38×10^{20}	1.49×10^{20}	1.60×10^{20}	1.71×10^{20}	1.79×10^{20}	1.85×10^{20}

during 2000–2007, compared with other exergy input. As is well known, Ex, Co support are the basic and vital to sustain the national economy, and their normal operation would be interrupted if there were problems, especially environmental problems, in the extended exergy input. More expenditure and recognition should be invested into these large but vulnerable sectors in future, so as to make a resilient cycle based on social-economic-environmental harmony.

Both in the In and Tr sectors (see Fig. 3d,e), *CEC*, E_C and E_W had a relative equilibrium structure; for example, the proportion of *CEC* to total extended exergy was probably 1/2 in the In sector and 1/3 in the Tr sector, and E_C increased, reaching 21.6% and 27.6%, respectively, in 2007. Moreover, the percentage of E_R in 2007 reached 5.5% in the Tr sector, which was the highest in all sectors during the study period, revealing positive results from concerns and actions by the government of China for management and improvement of traffic pollutions.

The Te and Do sectors are terminal and consumptive, having different features compared with other sectors. Te provides service as well as environmental problems related to assignment and use of natural, capital and labor resources, and at the same time, Do produces labor depending on resource consumption, and also produces environmental and ecological impacts. Both of these sectors rely on material output from other foundational sectors. In this research, in order to escape from double accounting, we considered only *CEC* and E_R in the Do sector, and calculated the natural primary energy resources, E_W and E_C in the Te sector without E_R. Service in Te sector is provided to human's life demand, which will lead environmental influences accompanying by Do sector's consuming. Therefore, we suppose the environmental impacts are all owned to putting up in Do sector. The accounting results of extended exergy carriers in these two sectors are shown in Fig. 3f and g. E_W was the most dominant exergy carrier in the Te sector, with a range of variation from 95.0% in 2000 to 90.0% in 2007, illustrating the most important status of manpower. The economic investment replaced E_W to obtain higher economic efficiency. The proportion of *CEC* and E_R in Do remained relatively stable, while both *CEC* and E_R had increasing investment in this sector, except for a two short periods. From 2001 to 2002, the net value of extended exergy had almost no change, due to nearly no variety on *CEC* and E_R, and the increasing tendency stopped in 2006 because of decreasing *CEC*, based on values acquired from statistical yearbooks.

3.3. Comparison between exergy and extended exergy by sector in 2007

Fig. 4 below demonstrates the clear difference between exergy, namely CEC, and extended exergy in seven sectors. In Fig. 4a, the interpolation between two indicators was not so distinctly different in Ex, Co and Ag sectors, with a range of 10–12% difference. At the same time, it was possible to distinguish differences in exergy and extended exergy values in the In, Tr and Te sectors, apparently showing that the first three sectors mainly provided output into

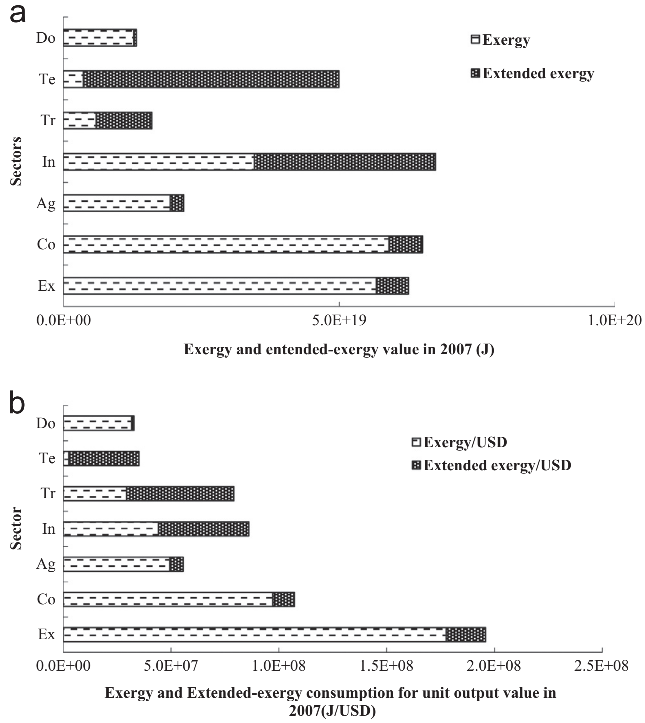

Fig. 4. (a). Comparison between exergy and extended exergy by sector in 2007, and (b). Comparison between economic productivity of exergy and extended exergy by sector in 2007.

Table 7
Comparison of Norway, UK, Italy, Province of Siena and China on Exergy/wh and Exergy/USD.

Area	Year	Exergy/wh (J/wh)	Exergy/USD (J/USD)
Italy	1998	2.36×10^{8}	1.82×10^{7}
Siena in Italy	2000	2.53×10^{8}	1.69×10^{7}
Norway	2000	5.26×10^{8}	2.01×10^{7}
UK	2004	2.48×10^{8}	5.80×10^{6}
China	2000	5.19×10^{7}	4.18×10^{7}
	2001	5.39×10^{7}	4.02×10^{7}
	2002	5.70×10^{7}	3.92×10^{7}
	2003	6.20×10^{7}	3.81×10^{7}
	2004	6.74×10^{7}	3.56×10^{7}
	2005	7.15×10^{7}	3.24×10^{7}
	2006	7.45×10^{7}	2.86×10^{7}
	2007	7.63×10^{7}	2.28×10^{7}

society depending on natural resource commitments, and the latter three sectors were influenced mainly by machining, manufacturing and human resources, and therefore demanding more capital and labor. Do was a special department, being the terminal consuming part, and was based more on use of products from other sectors, than on product creation by itself. The accounting criterion of Do indicated little distinction about exergy and extended exergy.

In Fig. 4b, USD refers to the output value in the corresponding sector, meaning, for example, that in the Tr sector, the money was the whole income in transportation field, and in the Do sector, it was the total labor cost paid, and in other sectors USD stands for the industry output value that transferred into the social and economic areas. The significance of Exergy/USD or Extended exergy/USD can be explained as one unit of economic output that relies on or reflects the amount of exergy depletion, therefore, the higher the value was, the lower the input–output conversion efficiency was. The results showed Ex was the most inefficient one among the seven sectors with its value at 1.8×10^{8} J/USD of Exergy/USD and 2.0×10^{8} J/USD of Extended exergy/USD, for Co and In, respectively. Tr had the second-largest level of Extended exergy/USD in 2007, ranging from 1.1×10^{8} J/USD to 7.9×10^{7} J/USD. Te and Do were the two highest efficiency sectors in extended exergy accounting, with values of only 3.5×10^{7} J/USD to 3.3×10^{7} J/USD, respectively, reflecting efficient economic outcomes in the terminal processing parts of the whole society.

3.4. Equivalent exergies of labor and capital for different societies

Based on the EEA method, calculating the total natural resource exergy quantity in the whole Chinese social system and labor input statistics during 2000–2007, the labor production efficiency value was estimated at 5.19×10^{7} J/wh (wh is the abbreviation of work-hour) in 2000 upwards to 7.63×10^{7} J/wh in 2007. Table 7 shows the variation trend of this index in the period of study, and the comparison with other previous studies of different societies. The labor production efficiency value was 5.26×10^{8} J/wh in Norway in 2000 [38], 2.36×10^{8} J/wh in Italy in 1998, 2.53×10^{8} J/wh in Siena in 2000 [77], and 2.48×10^{8} J/wh in UK in 2004 [30], all exceeding the value for China in the same years, although the values steadily improved in China during the period 2000–2007.

Net input of resource exergy pro-capite to the Chinese society, an economic value produced by unit natural substance, is a key indicator in measuring the interconnection between available extended-exergy resource and social economy. This index represents the transfer ability from raw materials into monetary value, which usually represents the efficiency of resource consumption. The value of this index amounted to 4.18×10^{7} J/USD in 2000 and dropped to 2.86×10^{7} J/USD in 2007, with the downtrend accelerating especially after 2003, as shown in Table 7. Although improvement in transition efficiency from material input into economic value output was apparent in recent years, there was still a large disparity compared with some high efficiency countries in former studies: 2.01×10^{7} J/USD in Norway in 2000, 1.82×10^{7} J/USD in Italy in 1998, 1.69×10^{7} J/USD in Siena in Italy in 2000 and 5.80×10^{7} J/USD in the UK [30,38,77]. Nevertheless, there is still opportunity to increase transforming efficiency of net resource consumption pro-capite input in China.

4. Discussion

The extended exergy of natural resource consumption in China increased from 2000 to 2007 at an ever faster rate. Meanwhile, as capital and manpower input started to assume a greater significance in the societal picture, the growth rate of extended exergy accelerated, confirming that EE can be a relevant factor in socio-ecological systems analysis.

The increase of the labor production efficiency and the decrease of the net input of resource exergy pro-capite signal conversion from material exergy to dematerialized output. But in order to develop along a less unsustainable pattern, production, tertiary and domestic sectors should devote more efforts to improving productivity rather than aim for increased throughput with resulting massive resource depletion.

Natural resource analyses are performed regularly by state agencies and included in official statistical reports. Usually, these analyses tend to be quantified in terms of monetary values or mass flow rate analysis. However, in view of the growing discomfort of analysts with resource evaluations based on monetary or mass-throughput metrics, the use of extended exergy analysis emerges as the tool needed to evaluate the synthetic consumption of natural resource in China from a point of view that encompasses environmental, economical and social aspects.

Societal extended exergy analysis is considered as an effective method to reveal the energy quality and degradation in the resource conversion process at the national level [73]. The comparison of social resource accounting between different societies by using diverse indices can not only be used to diagnose the quality of production conversion co-efficiency, assess environment impact and ecological dysfunctions [26,38], but also can reveal the intrinsic societal resource utilization structure and its temporal and spatial allocation.

Whereas the traditional exergy analysis is based on exergy biophysics, extended exergy is intended to highlight the primary production factors, labor, capital, exergy, materials and environmental remediation [2,77]. This approach is a systematic attempt to integrate into a unified coherent formalism both cumulative exergy consumption and thermo-economics, and constitutes a generalization of both, in that its framework allows for a direct quantitative comparison of non-energetic quantities like labor and environmental impact [2]. EEA provides a good measure of the amount of primary exergy resources "used up" in the life cycle of a material or immaterial commodity [77], and indicates the comprehensive statement of socially necessary, economically feasible and environmentally friendly cost.

After the restructuring of the industrial sector in China, since its entry into the 21th century, the enormous demands for products such as private cars and energy-consuming electronics, higher material demands on the one hand highly improved average life standards, and on the other hand extremely aggravated natural resources depletion, especially for non-renewable material resources. The only solution to avoid an energy crisis, especially for non-renewables, is to increase both conversion and end-use efficiency, and better exploit renewable energy. In addition, China suffers from a contradiction between its large global energy use and its low pro-capite energy resource base: a contradiction that may well restrict the national development in the social and economic fields.

On all accounts, it can be concluded that EEA results are very reasonable and enlightening for the resource policy management of the whole country. As mentioned above, EEA is an integration of life cycle analysis, classical exergy analysis, cumulative exergy analysis, and embodied energy analysis. It is completely and genuinely a second-law metric. Whereas the accounting of E_R still poses some problems, it was included in *CEC* as a part of cumulative exergy consumption to account for environmental cost. We are well aware of the fact that the economic dimensions of environmental pollution and ecological destruction cannot be simply evaluated in terms of capital investment because some long-range time and space interactions cannot be characterized solely in terms of monetary units, but the amount of work needed to attain a complete and reliable classification of all possible "remediation processes" and compute a genuinely EEA-based E_R is still prohibitive and must be postponed to future studies.

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